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April 1995

## **Construction Productivity Advancement Research (CPAR) Program**

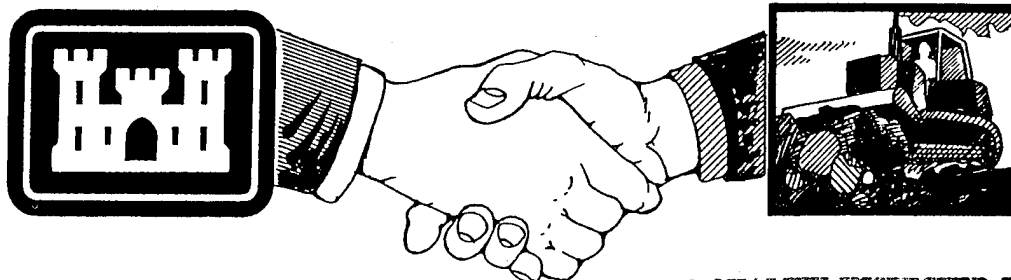
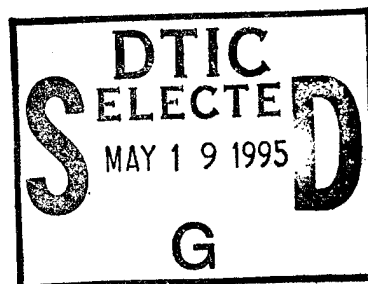
**Development of a Cost-Effective Demountable Interior  
Wall System Using Innovative Designs and Materials**

by

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Jonathan C. Trovillion

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**A Corps/Industry Partnership To Advance  
Construction Productivity and Reduce Costs**

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## Foreword

This research was performed for the Directorate of Research and Development, Headquarters, U.S. Army Corps of Engineers under the Construction Productivity Advancement Research (CPAR) Program; Work Unit "Building Assemblies System (BAS)"; and under Funding Authorization Document (FAD) 1-002443, dated 27 September 1989. The technical monitor was Charles Gutberlet, CEMP-ET.

The work was conducted through a Cooperative Research and Development Agreement (CRDA) between the Engineering and Materials Division (FM) of the Infrastructure Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL) and Williams Building Diagnostics, Inc. (WBD), Maple Glen, PA. The USACERL principal investigator was Richard G. Lampo, CECER-FMS, and the WBD principal investigator was Mark F. Williams. Appreciation is expressed to the following personnel for their significant roles in conducting the experiments, evaluating the results, erecting the demonstration construction, and/or assisting in the preparation of this document: Mario Salazar, Gregg Blaszk, Jerry Abner, Julius Hufmeyer, and Donald Currie, USACERL, and Mary Straney, Murray Libersat, Peter Johnson, Keith Stellabot, and Michael Knox from WBD, Inc. Dr. Paul Howdysshell is Chief, CECER-FM, and Dr. David M. Joncich is Acting Chief, CECER-FL. The USACERL technical editor was William J. Wolfe, Information Management Office.

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# 1 Introduction

## Background

Under the Construction Productivity Advancement Program (CPAR), the U.S. Army Corps of Engineers strives to improve the productivity and competitiveness of the U.S. construction industry by partnering with the commercial sector to develop new construction technologies. During renovation or demolition, for example, when a conventional partition wall made of studs and gypsum drywall is demolished, most, if not all, of the materials are discarded as waste. In such cases, a demountable, relocatable wall system, built from reusable or recyclable components, may offer a more productive, efficient, environmentally friendly, and cost-effective alternative to traditional construction methods. Such a system may offer multiple benefits if a board material such as gypsum fiberboard, which is partially composed of recycled newsprint, is used in its construction.

Although several demountable wall systems are currently commercially available, they offer no cost advantages over conventional drywall partition systems. Typically, the additional cost of these systems is not justifiable unless the user plans to relocate the partitions several times over the expected life of the facility. Moreover, many of these systems use gypsum drywall sheathing, which is vulnerable to mechanical damage.

The durability of a wall system is directly related to the durability of the individual components: studs, sheathing boards, fasteners, etc. During the past 5 years, new high-performance sheathing boards such as gypsum and cementitious fiberboards have become available in the United States. These boards offer some advantages over conventional gypsum drywall, which is used in most U.S. interior wall construction. Gypsum fiberboard and cement fiberboard have greater mechanical strength than drywall, allowing alternative fastening methods in their application. New fastening methods open the door to innovative interior partition systems that have the look, feel, and stability of a stud frame/conventional drywall sheathing wall assembly, but are also demountable and relocatable. These features may make a relocatable wall system more cost competitive than conventional drywall. The Building Assemblies System (BAS) is one example of such innovation. The principals of Williams Building

Diagnostics, Inc. (WBD)\* were awarded patents for the first version of this system in 1989 and 1990.\*\* However, full-scale mockups and tests of the patented concepts had not been conducted.

A proposal was submitted to the U.S. Army Corps of Engineers CPAR Program to refine and validate the original patent concepts of the BAS system. (Appendix A gives further information on the CPAR Program.) A 2-year project was approved for execution beginning in 1990 to further develop and validate the initial BAS concepts. The industry partner for this CPAR project was Williams Building Diagnostics (WBD)\*\*\* and the laboratory partner was the U.S. Army Construction Engineering Research Laboratories (USACERL).

## Objectives

The overall objective of this CPAR project was to develop the initial concepts for a demountable and relocatable wall-system design into a complete wall assembly ready for commercialization and marketing based on performance testing and validation of full-scale fabrications. Another objective of this study was to compare the BAS demountable and relocatable interior wall partition system for performance and cost competitiveness with conventional drywall construction.

## Approach

The first step in this project was to survey sheathing boards available in the United States that might have sufficient mechanical strength to be able to dado the edges for the spline connectors. Since attachment of the stud to the sheathing board also required screw fasteners, tests were performed on selected sheathing boards to determine fastener pull-out strengths. Scale and full-sized mock-up constructions of the wall system were built to refine the stud design and attachment details. A full-scale demonstration office complex was constructed using the developed design.

Lessons learned from this initial demonstration construction led to a system redesign incorporating an entirely new stud and attachment configuration. The new stud design was optimized for strength and efficient use of materials. Laboratory tests were

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\* Formerly Kenney, Williams and Williams, Inc. (KWW) at the initiation of this project.

\*\* Patents no. 4,833,849, dated 30 May 1989, and no. 4,897,976, dated 6 February 1990.

\*\*\* WBD, Inc., 945 Tennis Avenue, Maple Glen, PA 19002.

performed on the new attachment techniques and a second demonstration construction office complex was constructed using the redesigned system.

## Scope

The system refinement and redesign effort required at this stage of the project limited the scope of this study. Additional system refinements and testing, e.g., tests for fire resistance and sound transmission, will be necessary before the system can be commercially marketed.

## Mode of Commercialization and Technology Transfer

The responsibility for manufacture and marketing of the BAS wall system will be retained by WBD, Inc. through license agreements between WBD and other interested parties. Assuming the BAS wall system becomes commercially available, use of this system by the Army would impact Corps of Engineers Guide Specifications (CEGS) 10615, *Demountable Partitions* and CEGS-06100, *Rough Carpentry: System Description and Goals*.

## 2 System Description and Goals

### Description of the Building Assemblies System

The BAS concept consists of a prefabricated, demountable interior wall system consisting of wallboard panels, specially designed metal stud profiles, mounting hardware, and an innovative panel-joint finishing method. The system is intended to be easily assembled and disassembled using either standard or specially designed handheld tools. The BAS concept is to provide an economical, efficient, durable, panelized wall system using high-performance board materials assembled in an innovative manner.

The BAS design concepts incorporates 16-in., 24-in., and 48-in. boards (or any combination of these), fastened to metal studs fabricated in a distinctive shape.\* Panels can be installed in a staggered or non-staggered manner. Panels can be removed to provide wall cavity access. The board joints may be left unfinished for a modular appearance or finished to present a monolithic appearance. Even when the joints are finished, the system concept will allow components to be disassembled and reused with special finishing tools described later.

BAS should be suitable for small and large construction projects and all types of building—residential, commercial and institutional, among others.

### BAS Performance Goals

WBD reviewed the original BAS design concepts in terms of performance requirements for an interior partition system. The following performance criteria were established:

- *Economical use of high-performance board materials*—Select the lowest cost sheathing board that will function with the innovative assembly methods. Even if higher-performance/higher cost (than gypsum drywall) boards are selected, the greater material cost could be compensated if the materials create a wall system that is easier and faster to construct.

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\* A metric table with conversions for standard units of measure used in this report appears on p 34.

- *Economical methods of assembly and disassembly (for relocation)*—If materials must cost more, the higher cost must be compensated by methods of assembly and erection that are economical, simple, and fast, to achieve the overall goal of cost competitiveness with conventional drywall construction (in terms of initial costs). Further life-cycle economies could be realized if the system could be easily disassembled and relocated two or more times over the expected life of the facility.
- *Appropriate structural performance and system durability*—The wall system must meet minimum code requirements for interior partition walls. Section 2309(b) of the Uniform Building Code requires that interior walls exceeding 6 ft in height shall not deflect more than 1/240 of the span with an applied load of 5 lb per sq ft.
- *Accommodation and ease of access to mechanical, electrical, and communications wiring and services*—The wall system shall have removable panels/sections that will provide ready access to the wall cavity and thus to the service utilities.
- *Suitable fire resistance*—The interior wall system shall have a minimum 1-hour fire rating when tested in accordance with ASTM E-119, "Standard Test Methods for Fire Tests of Building Construction and Materials."
- *Variety of finish material options*—The BAS wall system must accommodate common wall finishing systems such as paints and wallpaper.

### 3 Development of First-Generation (Alpha) Design

#### Alpha Design

After studying methods of panelized construction use in other countries, and surveying the market for partition systems, WBD developed the first version of the BAS to take advantage of the most desirable and current design features and to adapt those features to U.S. construction practices.

In selecting board materials for the first-generation BAS, WBD surveyed various partition board materials, including: wood (plywood), resin-bonded composite board, gypsum wallboard (paper-faced and glass fiber-faced), gypsum fiberboard, gypsum particleboard, cement fiberboard, and calcium silicate board.

#### *Selecting Board Materials*

The original, patented BAS design featured a dado milled in the vertical edges of the boards, a spline connector, and an offset, L-shaped metal stud (Figure 1). The dado-and-spline design was found to work best with wood particleboards, or those modified with gypsum or cement. Since the cement and gypsum particleboards were not readily available in North America, cement and gypsum fiberboards and gypsum drywall were considered. Gypsum fiberboard and drywall are relatively inexpensive products, while cement fiberboard is approximately four to five times more costly. Because of its cost, cement fiberboard was eventually dropped from consideration. The different sheathing boards are described in more detail below.

**Gypsum fiberboard.** This board is made of water, gypsum, and cellulose fibers subjected to high pressure to produce a sheathing material. The board has a homogeneous composition; i.e., fibers are uniformly distributed throughout. Recycled newsprint is a common source of such fibers. Perlite may also be incorporated into the mix to reduce the overall weight of the board. Gypsum fiberboard differs from traditional gypsum wallboard by its lack of laminated surfacing, better fire resistance, higher bending strength, and better resistance to impact. It can also be sanded, and it does accept veneer or other coating materials, including paint.

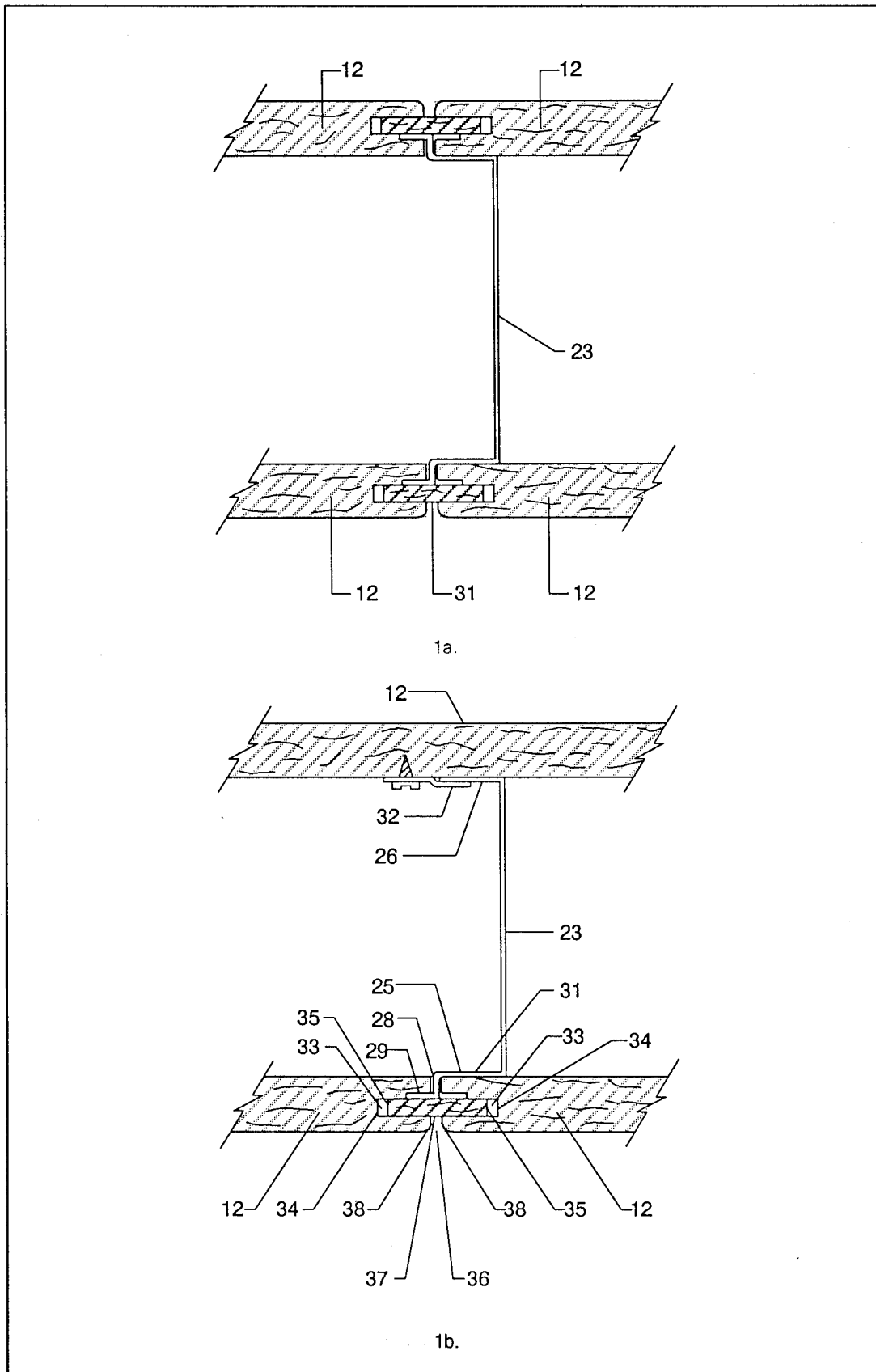


Figure 1. Original patented Building Assembly Systems (BAS) concepts. (a) cross-sectional view showing boards with dado milled edges and spline connector, (b) spline connector showing screw attachment to backside of sheathing board.

**Cement fiberboard.** This board is a mixture of cement, water, cellulose fibers, and additives used to regulate the setting time of the cement. The mixture, typically 70 percent cement and 30 percent fibers, is compressed and rolled into sheets. The resulting boards have a hard, smooth finish. Cement fiberboard possesses relatively good strength and density. It resists impacts better than gypsum-derived products, and resists biological attack by fungus or insects due to its high alkalinity.

**Standard Gypsum Wallboard.** This well-known construction board consists of a core of gypsum plaster surfaced with paper firmly bonded to the core. This board was included in the BAS program to provide a baseline for comparison to gypsum fiberboard.

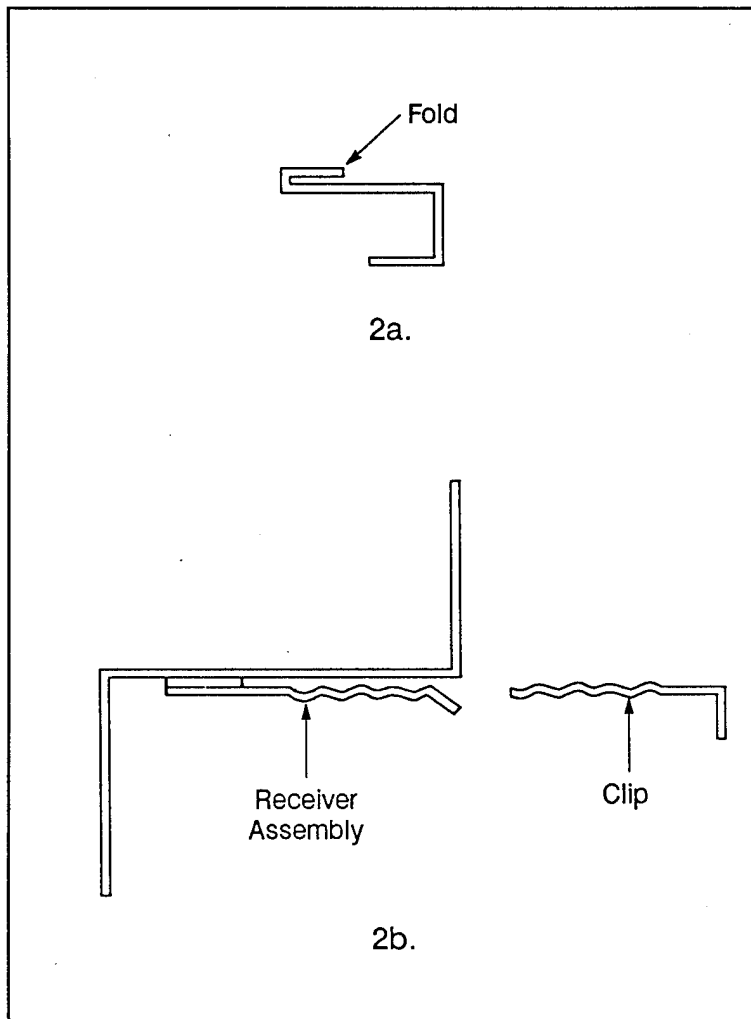
### **Stud Profile**

One of the most promising board materials was gypsum fiberboard, which included perlite as part of the matrix. Perlite reduces board weight and enhances fire resistance. However, perlite-modified boards were less dense than fiberboards manufactured without perlite and could neither be consistently milled nor support a spline connector.

Since the dado-spline design was unsuccessful with this board type, the spline approach was discarded. A new method of attachment was developed using a 3-in. corrugated metal clip that fits into a receiver assembly spot welded to the side of a specially designed, Z-shaped stud. Metal J-channels are placed on the vertical edges of the boards. The metal clips are attached to the sheathing boards by slipping one edge into a fold in the J-channel. One leg of the Z-stud is fastened to the board by screw fasteners and the other leg slipped into the fold of a J-channel on the edge of the sheathing board on the opposite side of the wall (Figure 2). Figure 3(a) shows an exploded view of a staggered panel wall assembly and Figure 3(b) shows the connector details. A series of small-scale models were used to simulate actual system connections and provide an efficient way to develop and refine the joining methods.

### **Testing Boards for Fastener Pullout Resistance.**

With the Z-stud design, fasteners were not driven through the face of the board into the stud, but rather through the stud into the board from the back side. To determine the fastener pull-out resistance with candidate boards, pull-out tests using 3/8-in., No. 7 sheet metal screws and 1/2-in., No. 7 self-tapping screws were done on 1/2-in. and 5/8-in. gypsum drywall, 1/2-in. gypsum fiberboard, and 7/16-in. cement fiberboard.



**Figure 2. Metal accessories and Z-stud: (a) J-channel accessory for board edges, (b) specially designed Z-stud with receiver and clip used to attach removable panels.**

To lessen the possibility of stripping out board material by overtightening the fasteners, each fastener was carefully screwed into the samples using a handheld screw- or nut-driver. Each fastener was pulled from the sample at a rate of 0.10 in. per minute with a universal testing machine. Figure 4 shows the test fixture. (Preliminary tests at 0.05, 0.10, and 0.15 in. per minute showed that the results were not rate-dependent within this range.) The force required to pull out each fastener was recorded. Tests were performed for each fastener and board type (Table 1).

A structural analysis of the wall system using the fastener pull-out test results indicated that an excessive number of fasteners would be required to assemble a wall with adequate structural integrity (relative to UBC Section 2309(b) requirements). With the exception of cement fiberboard, board samples were significantly damaged by direct fastening, such that the same hole could not be used again. This means that different points of attachment would have to be used during any reassembly. In

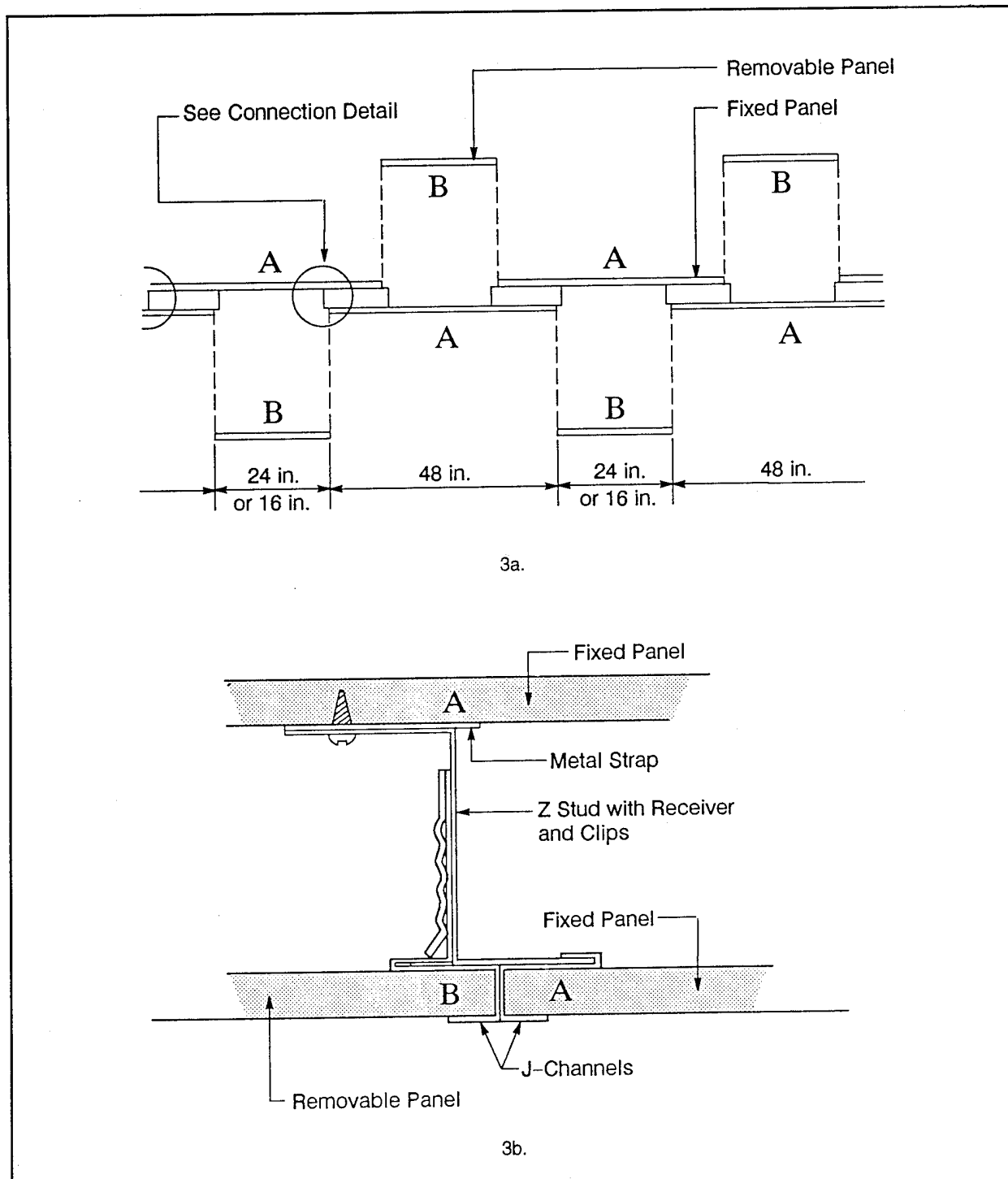
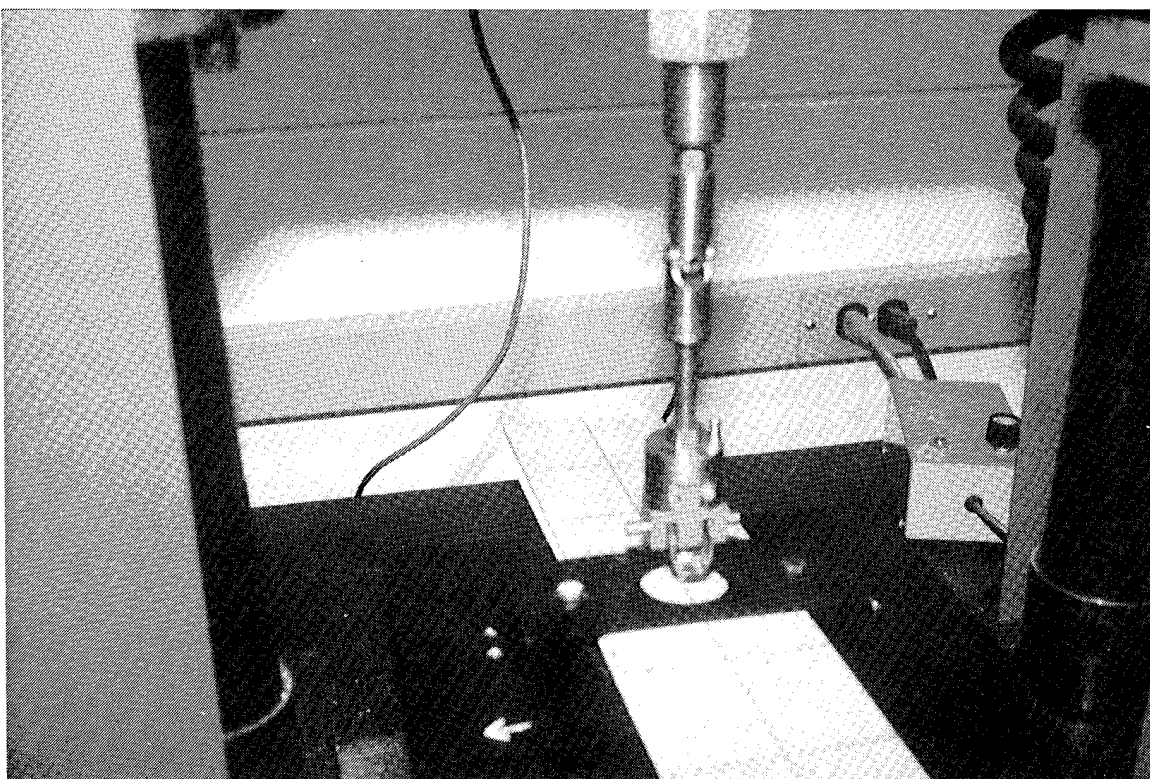
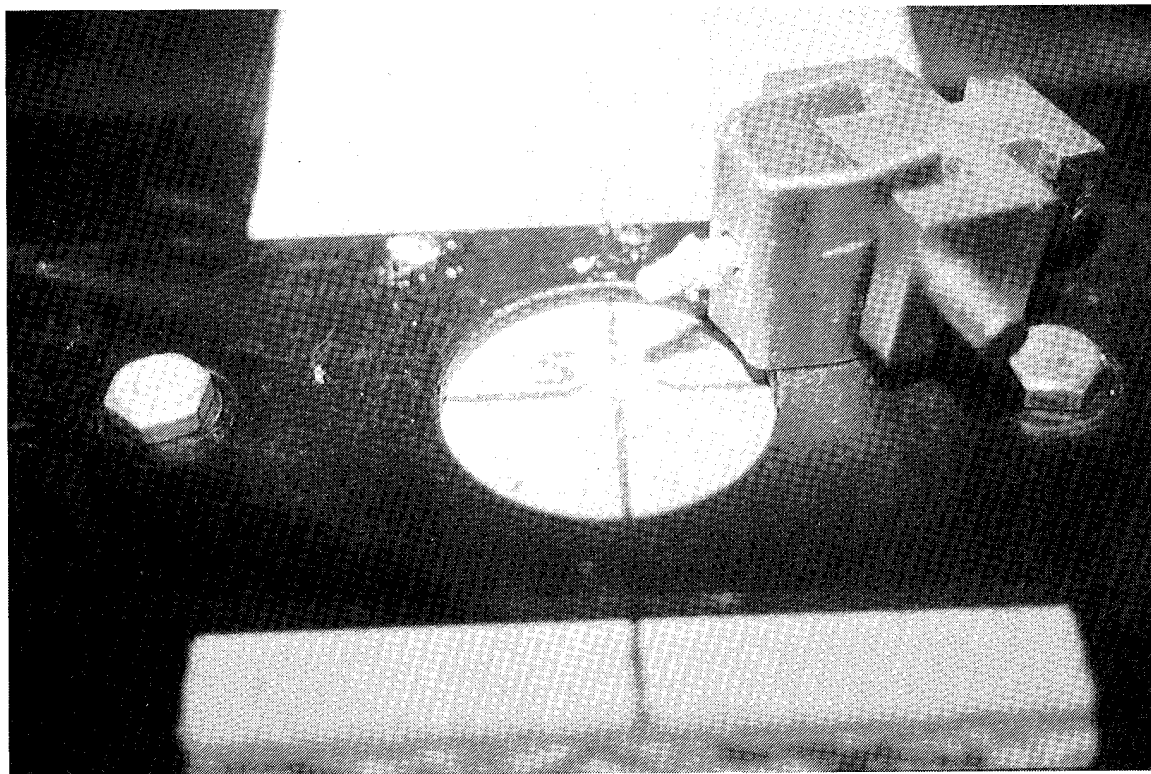


Figure 3. Exploded view of staggered panel BAS wall assembly: (a) overall view, (b) connection details.

addition, during actual system assembly at a construction site, the fasteners would be prone to overtightening, causing damage to the board material. When overtightened, the fastener strengths would undoubtedly be less than the values given in Table 1.



4a.



4b.

Figure 4. Test fixture used to perform the fastener pull-out tests: (a) overall view, (b) close-up of fixture.

**Table 1. Pull-out strengths of sheet metal screws and self-tapping screws in various sheathing boards.**

Sheathing Board	Fastener Type	Number of Tests	Average Pull-out Test Load (lb)	Standard Deviation
1/2-in. gypsum drywall	Sheet metal screw	15	6.6	1.8
	Self-tapping screw	14	5.6	3.0
5/8-in. gypsum drywall	Sheet metal screw	15	5.5	1.5
	Self-tapping screw	15	6.3	2.8
1/2-in. gypsum fiberboard	Sheet metal screw	13	24.1	3.2
	Self-tapping screw	14	39.8	8.2
7/16-in. cement fiberboard	Sheet metal screw	14	44.8	7.5
	Self-tapping screw	15	81.8	22.5

**Table 2. Pull-out strengths of self-tapping screws in 20, 22, and 26 gage metal strips adhered to various sheathing boards.**

Sheathing Board	Strip Gage	Number of Tests	Average Pull-out Test Load (lb)	Standard Deviation
1/2-in. gypsum drywall	26 gage	15	30.9	4.1
	22 gage	15	35.5	7.0
	20 gage	14	46.0	4.7
5/8-in. gypsum drywall	26 gage	15	34.7	4.1
	22 gage	15	39.0	5.8
	20 gage	15	56.1	8.0
1/2-in. gypsum fiberboard	26 gage	15	58.0	5.9
	22 gage	15	64.5	8.5
	20 gage	14	70.3	9.6
7/16-in. cement fiberboard	26 gage	15	67.9	11.4
	22 gage	15	86.7	11.3
	20 gage	15	106.3	15.4

To overcome this difficulty, strips of sheet metal were adhesively applied to the backs of boards using standard construction grade wall adhesive to provide a more substantial base for fastener attachment. In tests, samples of 20-, 24-, and 26-gage metal strips were attached to the board materials with a commonly used drywall adhesive. Half-in., No. 7 self-tapping screws were then installed into the strips and pull-out tests were performed as above. Tests were done for each fastener, board type, and gage of metal strip (Table 2). Considering the fastening strengths needed to assemble an interior wall system that would meet UBC Section 2309(b) requirements, the fastener pull-out test results indicated that 20-gage metal strips would perform satisfactorily in the system design.

## Construction of the Alpha Mock-up

### System Deflection Tests

After the pull-out tests were completed, prototype "alpha" wall sections were constructed at the WBD site and tested to assess their resistance to panel deflection using ASTM E-330, "Standard Test Method for Structural Performance of Exterior Windows, Curtain Walls and Doors by Uniform Static Air Pressure." Three BAS sections were constructed with gypsum fiberboard and galvanized, 20-gage Z-studs. Two sections were faced with 16-in. and 48-in. alternating panels, one of which included a door. A third section was built with 24-in. and 48-in. alternating panels.

As a control, one wall section was constructed with conventional 20-gage C-studs and 1/2-in. gypsum wall board according to industry standards. Half of this section had 16-in., on-center stud spacing and the other half had 24-in., on-center stud spacing. When tested at 6.24 lb per sq ft, in accordance with ASTM E-330, BAS panel deflection was about half of that experienced by the gypsum drywall control section (Table 3). Both the BAS and conventional stud framing construction met the Uniform Building Code

**Table 3. Results of ASTM E330 System Deflection Test: test pressure  $\pm 6.24$  lb/sq ft.**

Construction Type*	Measurement Location	Negative Pressure Deflection	Positive Pressure Deflection	Span to Deflection ratio	
				Neg.	Pos.
Conventional stud framing, 20 ga. "c" studs 16-in. o.c.	4-ft panel between studs.	0.108 in.	0.112 in.	L/894	L/862
BAS construction, 20 ga. "z" studs 16-in. o.c.	4-ft panel between studs.	0.060 in.	0.060 in.	L/1608	L/1608
Conventional stud framing, 20 ga. "c" studs 24-in. o.c.	4-ft panel between studs.	0.134 in.	0.155 in.	L/720	L/623
BAS construction, 20 ga. "z" studs 24-in. o.c.	4-ft panel between studs.	0.107 in.	0.77 in.	L/902	L/1253
Conventional stud framing, 20 ga. "c" studs 16-in. o.c.	Directly on stud.	0.113 in.	0.108 in.	L/854	L/894
BAS construction, 20 ga. "z" studs 16-in. o.c.	Directly on stud.	0.060 in.	0.066 in.	L/1608	L/1462
Conventional stud framing, 20 ga. "c" studs 24-in. o.c.	Directly on stud.	0.073 in.	0.071 in.	L/1322	L/1359
BAS construction, 20 ga. "z" studs 24-in. o.c.	Directly on stud.	0.066 in.	0.072 in.	L/1462	L/1340

\*Conventional stud framing according to USG handbook. BAS construction for these tests was the "alpha design."

criteria, Section 2309(b), which requires that interior walls exceeding 6 ft in height shall not deflect more than 1/240 of the span with an applied load of 5 lb per sq ft.

### ***Attachment Methods for Removable Access Panels***

Screw fasteners were used in the "alpha" design to attach the fixed boards to the stud supports (Figure 3b). For removable panels, corrugated clips are attached to the J-channels mounted on the board's (vertical) edges. The removable panel is fixed into place by pushing the metal clip into the corrugated receiver assembly on the side of the Z-stud. The design concept allows the panel to be held in place by a friction fit of the clip in the receiver assembly, so the panel could be easily removed by prying the board away from the fixed wall (and the clips out of the receiver assembly).

### **Alpha Demonstration Construction**

Following initial mock-up tests at WBD, a demonstration construction of the BAS was built at the U.S. Army Construction Engineering Research Laboratories (USACERL) (Figure 5). This demonstration consisted of a rectangular area constructed of gypsum fiberboard and divided into three, 12x12-ft office spaces by two partitions. Each space contained a door. Two of the offices were connected by an inside door, and one had a

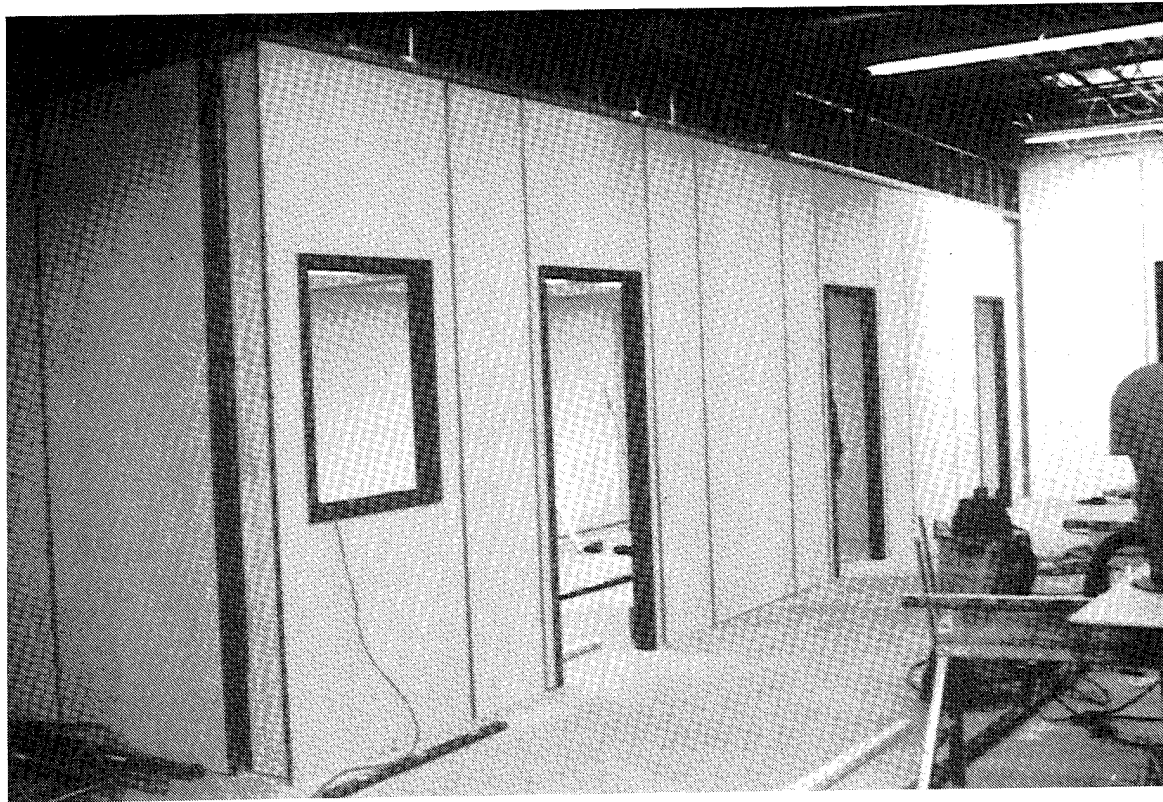


Figure 5. Three office spaces take shape in the "alpha" design BAS demonstration construction at USACERL.

window. The perimeter walls used one brand of gypsum fiberboard, while one of the dividing partitions used another. The remaining partition was built with 1/2-in. gypsum wallboard. Construction was done by USACERL carpenters overseen by a representative from WBD, Inc. One of the carpenters had personal experience installing some of the most popular premium demountable partition wall systems.

### **Lessons-Learned From Alpha Demonstration Construction**

This "alpha" construction was considered by those involved in its construction to be completely functional (the office areas are occupied and used daily) and structurally more stable and durable than other demountable wall systems, especially when the gypsum fiberboard was used. As erected, the system was not cost-competitive. An estimated cost of the "alpha" system construction was \$47.00 per linear ft, compared to approximately \$30.00 per linear ft for conventional drywall. The higher cost of the "alpha" system was largely attributed to the many system components (especially the J-channels for the board edges and the sheet metal strips for the fasteners) requiring considerable labor to assemble.

## 4 Development of Second-Generation (Beta) Design

### Beta Design

The J-channels and sheet metal strips were necessary in the "alpha" design system to facilitate the attachment of the sheathing boards to the support studs. Since this method of assembly proved to be too costly in practice, the system was completely redesigned. A desirable system would be one where the boards could be "snapped" on (and off) for assembly (and disassembly) as needed. It would also be beneficial if conventional steel C-studs could be used rather than specially fabricated Z-studs.

Double-sided tape and Velcro\* were examined as possible means to attach the boards to the studs. Neither of these ideas proved practical. The concept of using corrugated clips to attach the boards to the studs that could be easily attached to the boards and then locked into receptacles on the studs (as in the "alpha" system) seemed the most promising approach. A "beta" design system was developed where the corrugated clips were attached to the backside of the sheathing boards using a pronged plate connector (Figure 6). These attached clips then fit into slots in an innovative design "hourglass" stud (Figure 7) and "locked" in place. (Note that the "beta" design still required a specially designed stud.) Details of the "beta" design development and features follow.

### **Board Materials**

The revised new BAS design uses pronged plate connectors to attach retaining clips to the sheathing boards. This design depends on the ability of the pronged plates to firmly grip the sheathing boards. Cement fiberboard was not used in these tests because it did not appear to offer significant cost benefits. Boards used were 1/2-in. gypsum drywall, 1/2-in. gypsum fiberboard, and Class X fire-rated 5/8-in. gypsum drywall. The latter was considered, not only for its fire rating, but also to see if the glass fibers dispersed in the gypsum matrix of this board would enhance the pull-out strength of the pronged plates.

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\* Velcro is a registered trademark of Velcro USA, Inc., 406 Brown Ave., PO Box 5218, Manchester, NH 03108.

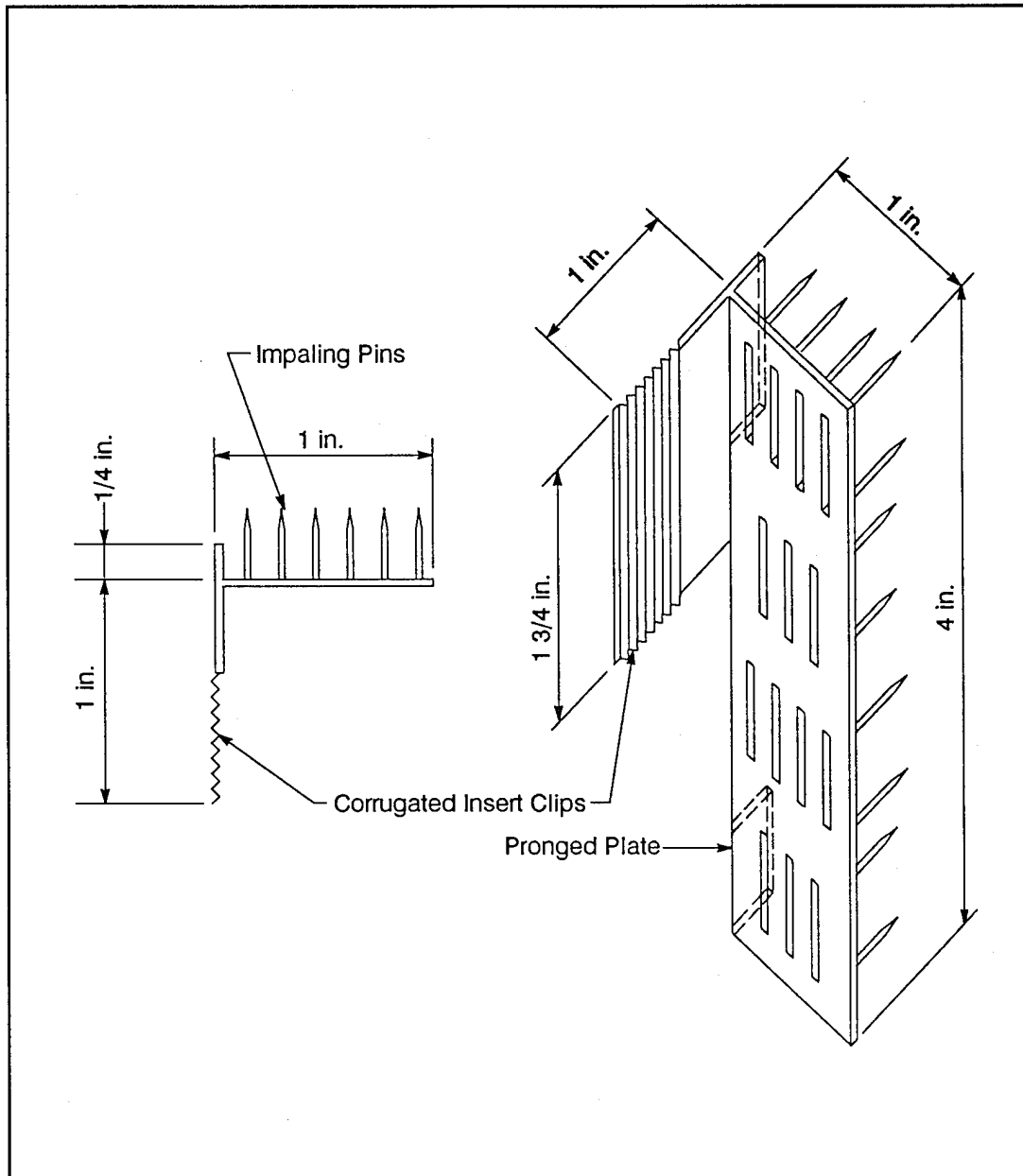
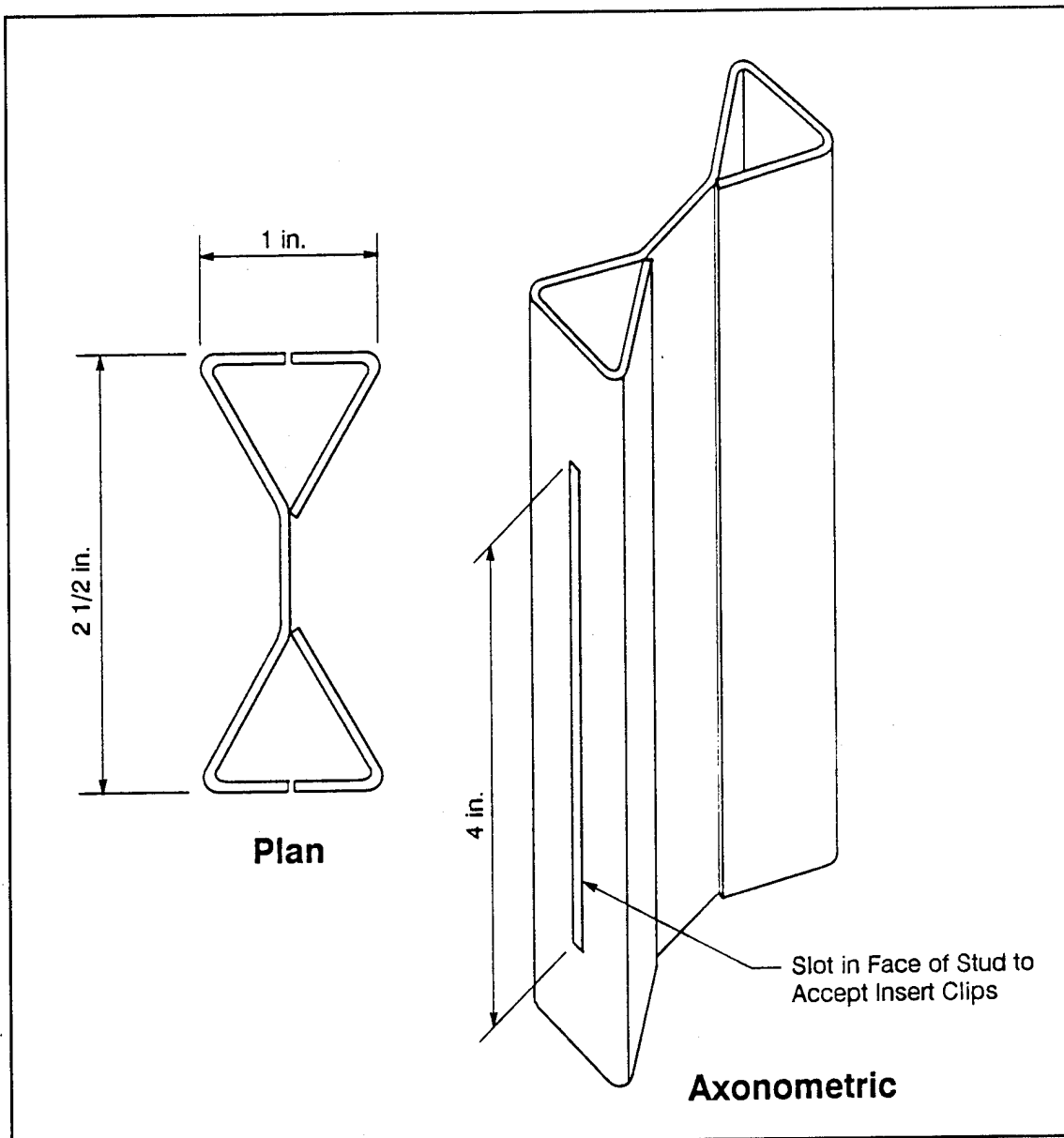


Figure 6. Pronged plate used to attach corrugated clips to the sheathing board.

### Stud Profile

The beta design of the BAS incorporated an innovative “hourglass” stud (so-called for its distinctive cross-sectional profile (Figure 7). Analysis of these studs (Appendix B) indicated that the unique shape made it stronger than C-studs of equal gage and size now in common use. The stud was designed to accept a special clip fastening system that should permit building boards to be removed and replaced repeatedly (Figure 8). The BAS stud can also accept standard screw fasteners, a valuable feature if screws are used at board joints. The system design that incorporates the “hourglass” stud has been patented.



### ***Tool Development***

To incorporate the design changes of the beta BAS, it was necessary to develop new tools for the manufacture and construction of the system (described in more detail below).

***Roll-forming equipment development.*** The complicated "hourglass" profile of the new beta stud posed a manufacturing challenge. Conventional shop equipment could not economically produce the required "hourglass" studs. A special roll-forming machine was designed and developed to manufacture the new stud (Figure 9).

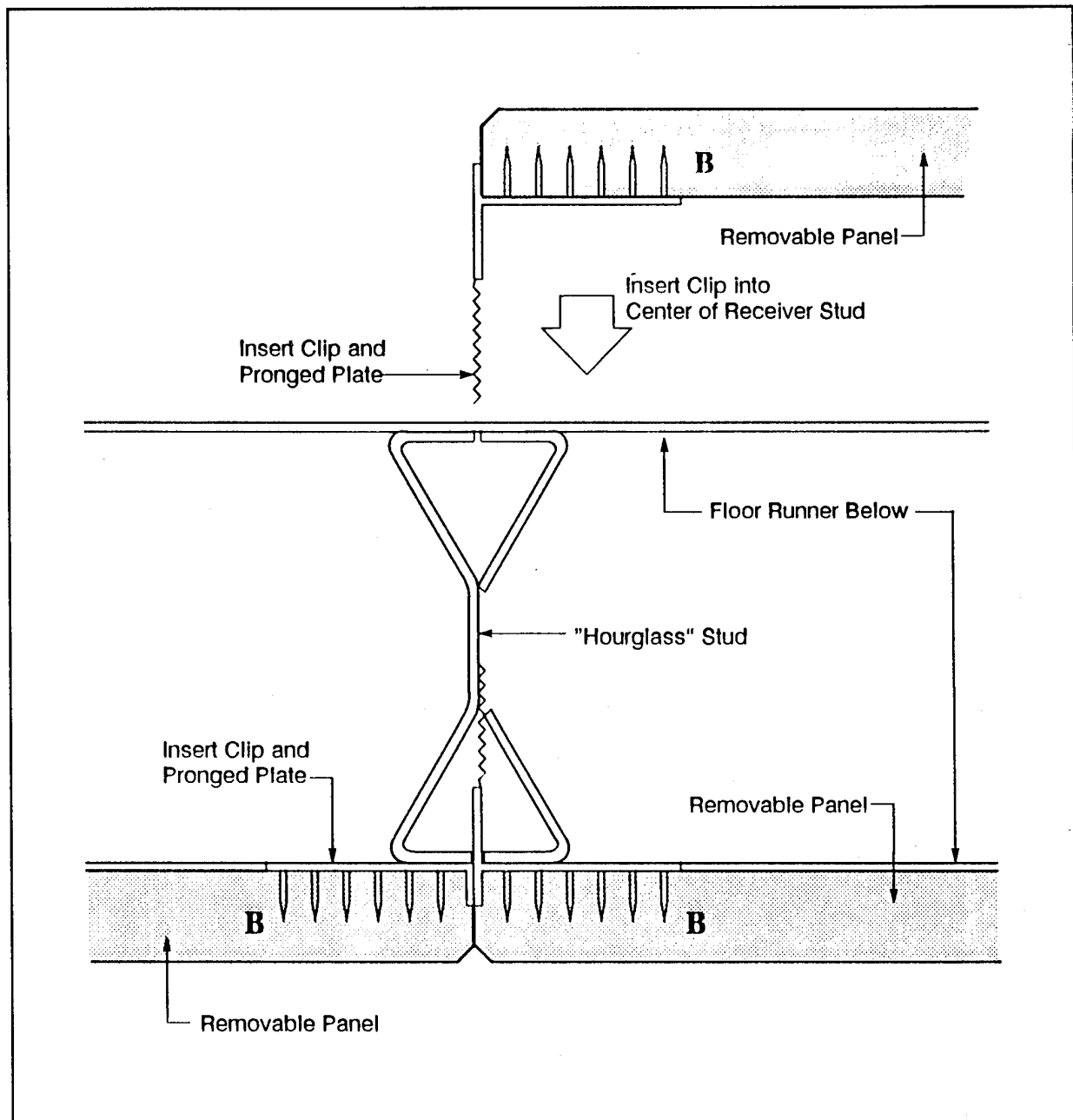


Figure 8. How sheathing boards are "locked" in place on the stud.

The roll-former machine can produce studs with minimal waste from flat or coiled steel stock. Currently, problems with the roll-forming machine create hourglass studs that do not always provide a firm grip of the corrugated clip. During prototype "mockups" and the demonstration construction (described later), drywall screws sometimes had to be used to keep the board from bowing away from the stud. It is expected that the roll-forming equipment could be adjusted or modified so that the fabricated stud will give the clips more uniform holding power. Once these problems are overcome, the

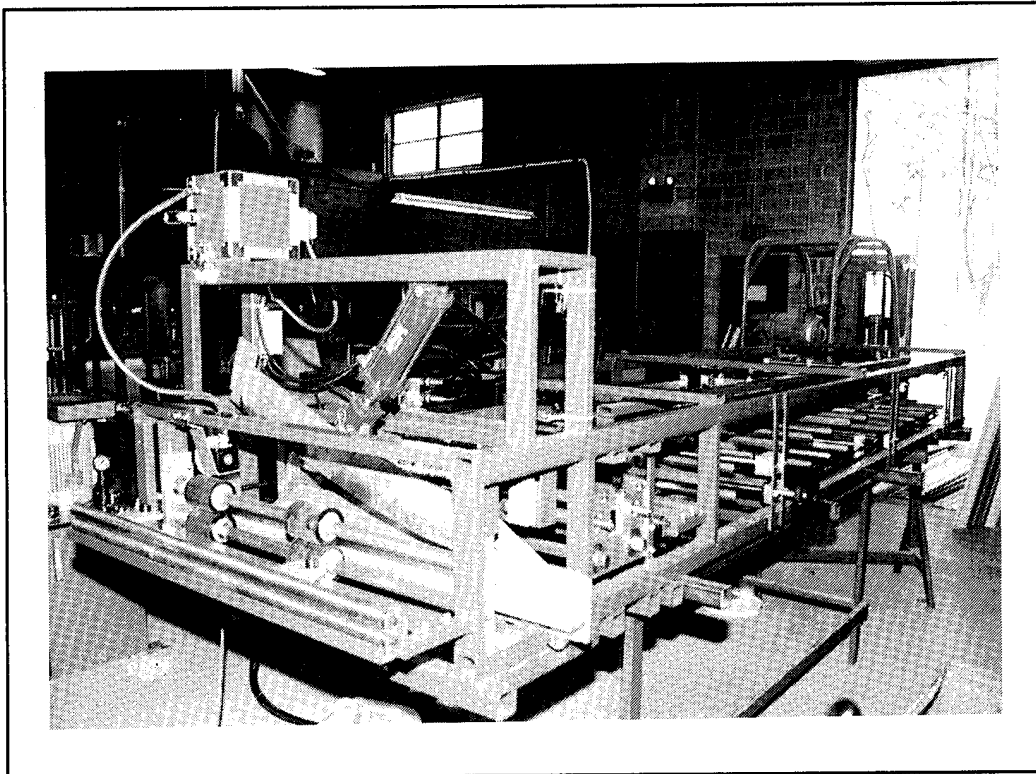


Figure 9. Prototype roll-forming equipment to fabricate the "hourglass" studs.

machine should be able to process 40 to 60 linear ft of steel stock (or 5 to 7, 8-ft BAS studs) per minute. The machine can be automatically controlled to enhance production efficiency.

***Pneumatic tool and tape gun development.*** A patented driver head to be used with a pneumatic hand tool was designed to install the pronged plates to most available wall board materials, including all types of gypsum-based boards (Figure 10). For finish work, an electrically heated tape gun was also developed to apply adhesive-backed tape to board seams (Figure 11). During system demounting, the same tool could be used to remove the tape/spackling without marring board surfaces. The heat gun can be fitted with different shaped applicator heads that allow the operator to cover flat seams as well as inside and outside corners with ease.

## Pronged Plate Tests

The clips used to connect the boards to the studs are held in place by a pronged plate driven into the boards. Tests were performed to evaluate the holding power of the pronged plates in various sheathing boards using the same basic procedures as for the screw fasteners (Table 4). Typically, the pronged plates pulled cleanly out of both the 1/2-in. and 5/8-in. gypsum drywall (Figure 12). However, when the pronged plates

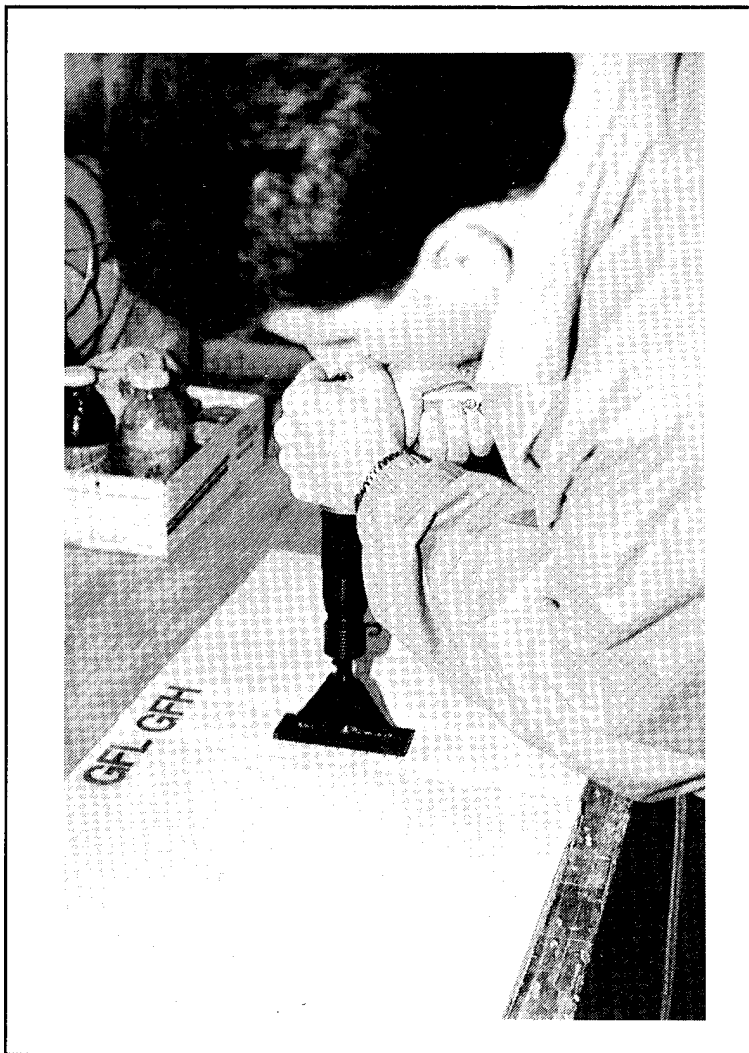


Figure 10. Pneumatic tool for installing the pronged plates.

were pulled out from the gypsum fiberboard, part of the fiberboard material came out with the plate (Figure 13). This indicates that the gripping power of the pronged plate on gypsum fiberboard is equal to or greater than the strength of the board material.

The force required to remove the pronged plates from the 1/2-in. gypsum fiberboard was three times that required for the 1/2-in. gypsum drywall and almost twice that required for the 5/8-in. Class-X drywall. A cursory structural analysis of the wall system (relative to UBC Section 2309(b) requirements) indicated that, for a gypsum fiberboard wall section 8- to 10-ft high, three pronged plate/clip assemblies would be needed at each edge of the board.

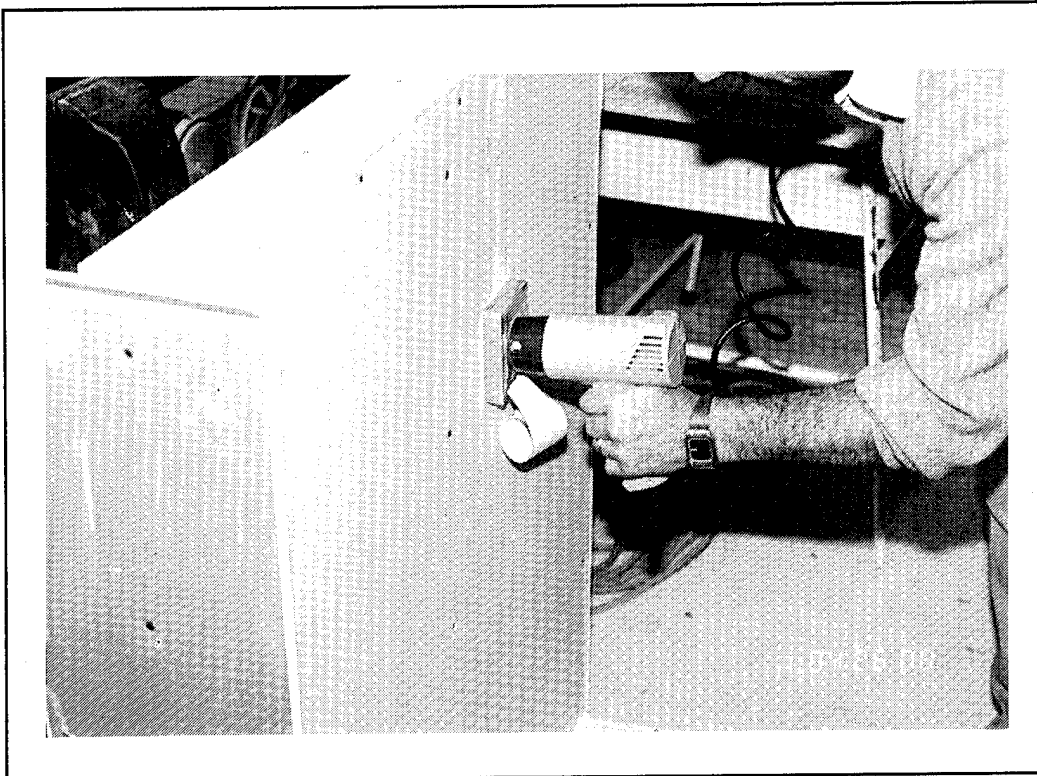


Figure 11. Special heat gun to apply adhesive-backed joint finishing tape.

Table 4. Pull-out strengths of pronged plate connectors in various sheathing boards.

Sheathing Board	Connector Length	Number of Tests	Average Pull-Out Test Load (lb)	Standard Deviation
1/2-in. gypsum drywall	3-in.	5	17.0	0.8
	4-in.	5	20.0	0.8
5/8-in. gypsum drywall (Class-X)	3-in.	5	32.0	4.7
	4-in.	5	34.0	10.3
1/2-in. gypsum fiberboard	3-in.	5	53.0	8.9
	4-in.	5	65.0	13.3

## Beta Demonstration Construction

To obtain a better idea of the actual system constructibility, another demonstration office complex was built at USACERL using the "beta" design system (Figure 14). For a direct comparison, one office room was built using conventional drywall construction (i.e., off-the-shelf steel C-studs and 1/2-in. thick gypsum sheathing) and an identically sized room was built using the "beta" BAS (using gypsum fiberboard sheathing).

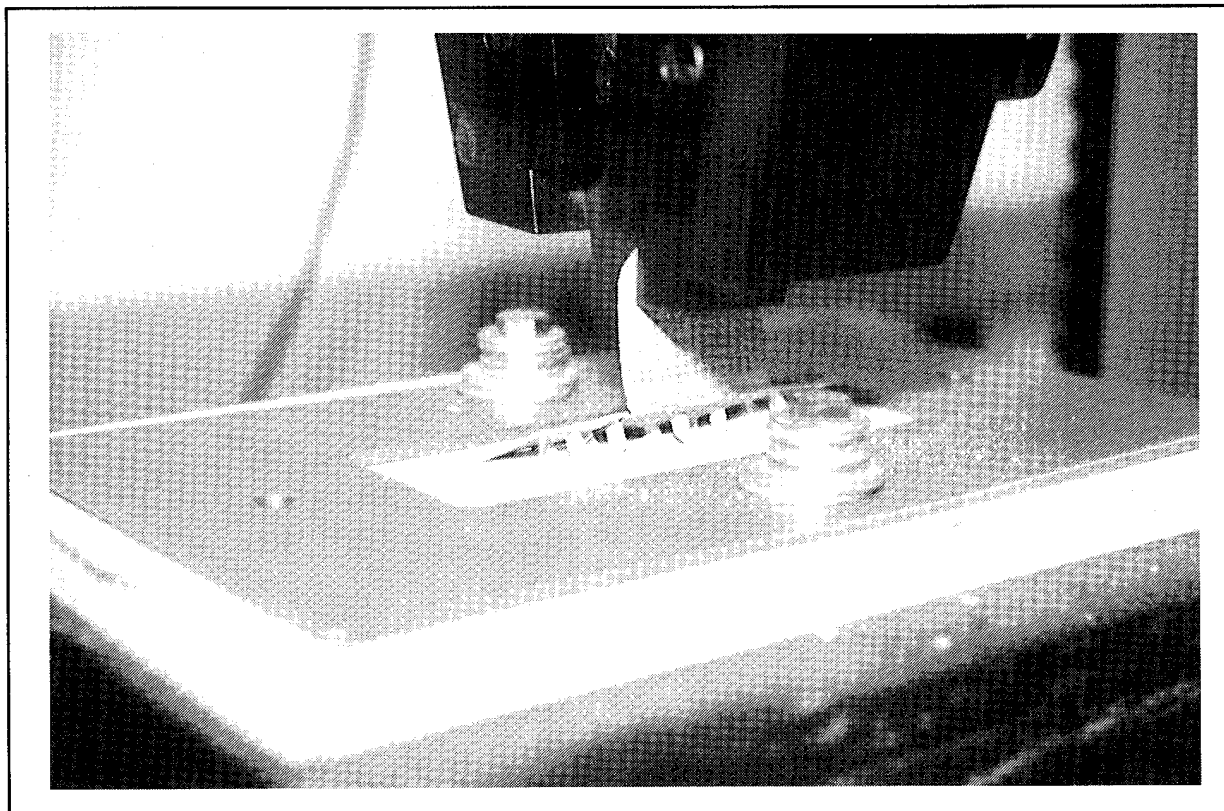


Figure 12. Typical failure of pronged plate as it is pulled out of gypsum drywall.

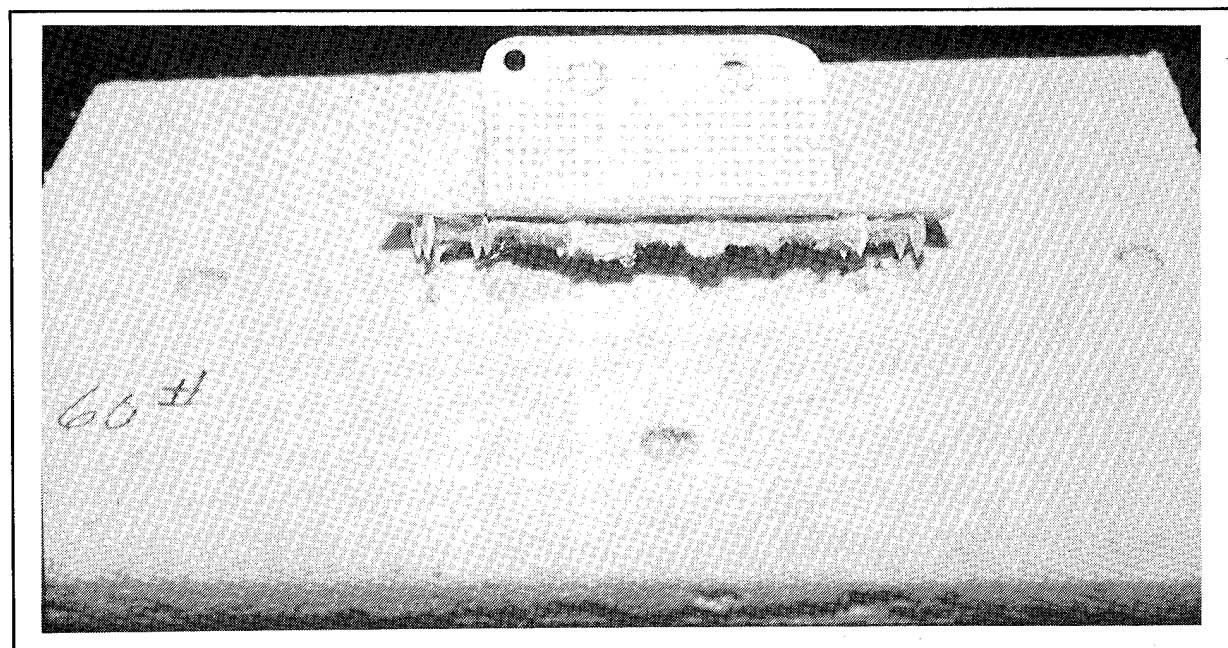


Figure 13. Part of the board material being removed as the pronged plate is pulled from gypsum fiberboard.



Figure 14. Wall section being lifted into place during "beta" design BAS demonstration construction at USACERL.

### Lessons Learned From Beta Demonstration Construction

While a detailed accounting of labor and materials to construct the two offices was not performed, enough information was collected to determine that, on a qualitative basis, the labor costs for erecting the "beta" design BAS were about the same as for erecting the conventional drywall system. Under the circumstances, comparison of materials costs could be misleading. Although exact figures are not now available, the fiberboard sheathing was several times more expensive than the standard gypsum drywall. However, the gypsum fiberboard was purchased in a small quantity (14 boards, 4-ft wide by 10-ft long), on a special order shipped from out-of-state. The hourglass studs were made especially for the demonstration construction using the prototype roll-forming equipment. Estimates derived solely from such a production run would be artificially high.

For the demonstration construction of the "beta" design BAS, gypsum fiberboards with tapered edges were purchased "off-the-shelf." A square edge board should be used to minimize the potential of edge breakage when installing the pronged plate fasteners. Some boards were installed where the edges were cracked during the pronged plate

attachment, possibly due to the tapered edges (Figure 15). The erected wall system was noticeably weaker at these locations.

Due to previously mentioned problems with the fabrication of the hourglass studs, the stud did not always provide a firm grip of the corrugated clip. At a few locations, drywall screws had to be used to keep the board from bowing away from the stud. It is expected that the roll-forming equipment can be adjusted or modified so that the stud will provide uniform holding power of the clips. Also, increasing the number of clips for a 10-ft high wall from three to five should provide a sturdier wall.

The demonstration construction went much smoother and quicker with the "beta" system than for the "alpha" system. In general, the "beta" BAS came much closer to meeting the original project goals than the "alpha" BAS.

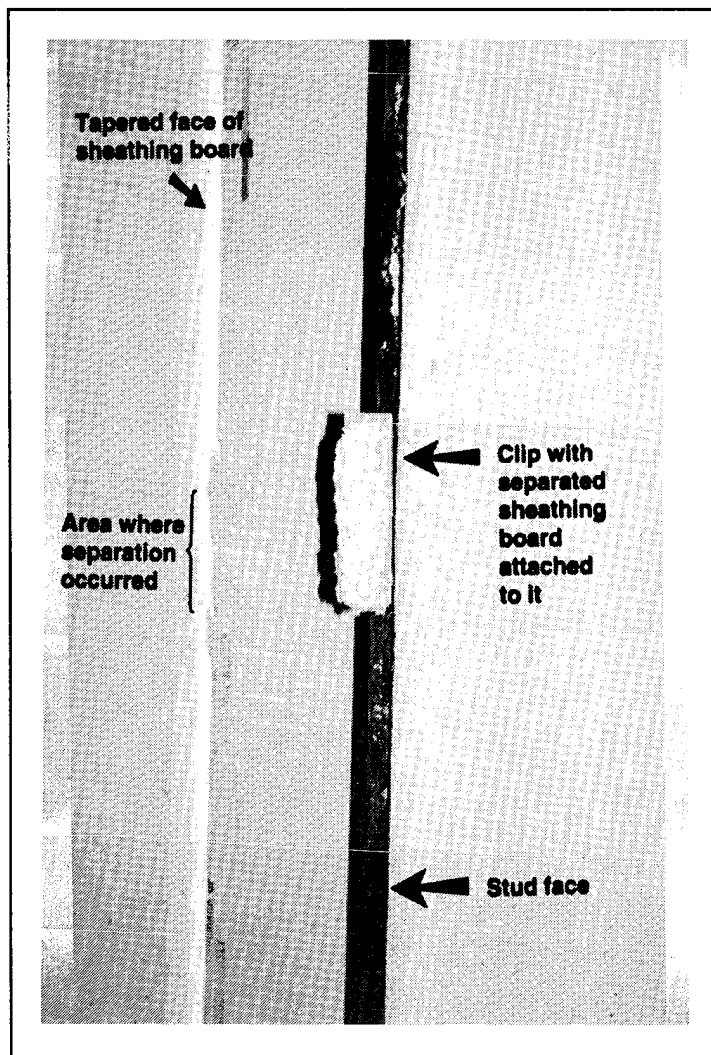


Figure 15. Location of board cracked during installation of the pronged plate and subsequent separation of the cracked piece during installation of the board to the stud assembly.

## 5 Conclusions and Recommendations

### Conclusions

The work performed as part of this cooperative effort developed and tested the performance of demountable and relocatable interior wall partition systems for performance and cost competitiveness as compared with conventional drywall construction. While a detailed accounting of labor and materials to construct the two offices was not performed, enough information was collected to determine that, on a qualitative basis, the labor costs for erecting the "beta" design BAS were about the same as for erecting the conventional drywall system. Cost considerations for materials are qualified by the fact that materials used in this study were obtained in small quantities and on special order, both circumstances that tend to skew materials costs upwards. The demonstrated "beta" design BAS has shown that the basic system concepts and potential benefits are still viable. However, several items (as described below) still need to be addressed before BAS is ready for full market commercialization.

### Recommendations

The results of the "beta" design demonstration construction should encourage further system development by the project partner, WBD, Inc. The following activities and issues need to be addressed before the BAS would be ready for commercialization and common use:

- *Roll-forming equipment*—Unless the hourglass studs are properly formed, they will not grip the corrugated clips sufficiently, resulting in a less sturdy wall. Adjustments or redesign of the manufacturing equipment should continue until studs of desired quality can be consistently fabricated. It cannot be overemphasized: the potential success of the entire system can be jeopardized by poor quality studs.
- *Sheathing board requirements*—Over the course of the investigation, the project evaluated and tested gypsum fiber boards from two different manufacturers, one of which is no longer in business. The strength and durability of the gypsum fiberboard sheathing is considered critical to success of the wall system. This is

especially true for the fastener holding strength. Therefore, it is recommended that the project partner coordinate its requirements with existing board manufacturer(s) to ensure minimum board qualities and requirements for use in the BAS. Preliminary investigation has shown that a major U.S. manufacturer of gypsum drywall has indicated it may begin manufacture of gypsum fiberboard. This would ease potential limitations associated with having a single source of supply.

- *Repeated disassembly/reassembly*—Although accounted for in the system design, repeated assembly and disassembly of the system has not yet been done on a full-scale basis. This feature needs to be tested and verified. One additional issue associated with both the board material and the “hourglass” stud is the holding force of the clip by the stud versus the holding force of the clip by the board. If the force holding the clip into the stud is greater than the force holding the clip into the sheathing board, the board will pull away from the clip during disassembly. This would leave the clip(s) locked into the stud, most likely causing severe damage to the board material and greatly reducing its chance for reuse.
- *Fire performance testing*—Considering the design and the materials used, the BAS should be able to meet appropriate fire rating for interior wall constructions. Appropriate fire resistance tests must still be performed before the BAS can be marketed. Tests should be performed in accordance with ASTM E 119 “Method for Fire Tests of Building Construction Materials.”
- *Sound transmission testing*—Although not as critical as the fire testing, sound transmission tests should also be performed. This information is important for office facilities. Sound tests should be performed in accordance with ASTM E 90 “Test Methods for Laboratory Measurement of Airborne-Sound Transmission Loss of Building Partitions.”
- *Economic assessment*—As the BAS is further developed, more detailed analyses and predictions concerning the system economics (i.e., costs and benefits) need to be done. Economic assessments should include life-cycle analyses relative to a *demonstrated* ability to reuse most of the system materials and components during multiple assembly and disassembly cycles.

The BAS concepts offer several features of potential benefit to the Army for both new and retrofit applications. Assuming the system passes the required tests and analyses and becomes commercially available, the BAS should be demonstrated under the Army’s Facilities Engineering Applications Program (FEAP) in actual construction at

selected Army installations. At the time of this writing, two installations have expressed interest in participating in such a demonstration.

**Metric Conversion Factors**

1 in. = 25.4 mm

1 ft = 0.305 m

1 lb = 0.453 kg

lb (force) = 4.448 joules/m (newtons)

1 ft-lb = 1.356 joules

lb/sq ft = 4.882 kg/m<sup>2</sup>

## References

American Iron and Steel Institute (AISI), *Specification for the Design of Cold-Formed Steel Structural Members* (AISI, Washington, DC, 1986 ed. with 1989 Addendum).

American Society of Testing and Materials (ASTM), E-90-90, "Standard Test Method for Laboratory Measurement of Airborne-Sound Transmission Loss of Building Partitions," in *1993 Annual Book of ASTM Standards*, vol 04.06 (ASTM, Philadelphia, PA, 1993)

———, E-119-88, "Standard Method for Fire Tests of Building Construction and Materials," in *1993 Annual Book of ASTM Standards*, vol 04.07 (ASTM, Philadelphia, PA, 1993).

———, E-330-90, "Standard Test Method for Structural Performance of Exterior Windows, Curtain Walls and Doors by Uniform Static Air Pressure," in *1993 Annual Book of ASTM Standards*, vol 04.07 (ASTM, Philadelphia, PA, 1993).

## **Appendix A: Construction Productivity Advancement Research (CPAR) Program**

CPAR is a cost-shared research and development (R&D) partnership between the U.S. Army Corps of Engineers (USACE) and the U.S. construction industry (e.g., contractors, equipment and material suppliers, architects, engineers, financial organizations, etc.) In addition, academic institutions, public and private foundations, nonprofit organizations, state and local governments, and other entities interested in construction productivity and competitiveness also participate in this program. CPAR was created by the Secretary of the Army to help the domestic construction industry improve productivity and regain its competitive edge nationally and internationally. This is done by enhancing USACE construction R&D programs with cost-shared industry partnerships. The objective of CPAR is to facilitate productivity-improving research, development, and application of advanced technologies through cooperative R&D programs, field demonstrations, licensing agreements, and other means of technology transfer.

The Federal Government is the largest single buyer of construction services. Technology advancements that improve construction productivity will reduce construction program costs. Projects not now economically feasible may become feasible due to lower construction costs. Such cost savings would accrue directly to the Federal Government's construction program, and would benefit the U.S. construction industry and the U.S. economy in general.

CPAR is intended to promote and assist in the advancement of ideas and technologies that will have a direct positive impact on construction productivity, project costs, and USACE mission accomplishments. R&D and technology transfer under CPAR is based on proposals received from educational institutions, the construction industry, and others that will benefit both the construction industry and the Corps of Engineers. The CPAR Program permits USACE to act on ideas received from industry, to cost-share partnership arrangements, and to rapidly implement successful research results through aggressive technology transfer and marketing actions. Section 7 of the Water Resources Development Act of 1988 (P.L. 100-676) and the Stevenson-Wydler Technology Innovation Act of 1980, as amended (15 U.S.C. 3710a et seq.) provide the legislative authority for the CPAR Program.

## Appendix B: Flexural Analysis of "Hourglass" Stud Design

Theoretical calculations assessing the flexural capacity of the special "hourglass" stud design were done independently by researchers at USACERL and an independent consulting engineer (a specialist in light-gage structural steel design). These calculations were determined in accordance with the "Specification for the Design of Cold-Formed Steel Structural Members" published by the American Iron and Steel Institute (AISI). Figure B1 shows how the stud was divided into elements during one such analysis series. The (USACERL) calculated "hourglass" stud capacity in flexure was 3660 in.-lb. An "optimization analysis" was also conducted by the independent consultant to determine stud dimensions and fabrication parameters that would make the "strongest" stud while making the most efficient use of metal from standard coil sizes.

As a check on the theoretical calculations, a four-point bending test was performed on one of the fabricated "hourglass" studs (Figure B2). The measured stud capacity in flexure was 4600 in.-lb. The discrepancy between the calculated and the measured values is primarily due to conservatism built into the specification. The unique shape of the "hourglass" stud necessitated certain assumptions regarding its buckling characteristics to use the specification. Based on the location of the neutral axis during the test (Figure B3), it appears that the "hourglass" stud is more resistant to element buckling than the specification predicts.

Based on the testing of the "hourglass" stud and manufactures' data for standard C-studs, the "hourglass" stud will outperform (in flexure) standard steel C-studs of comparable depth and thickness (gage).

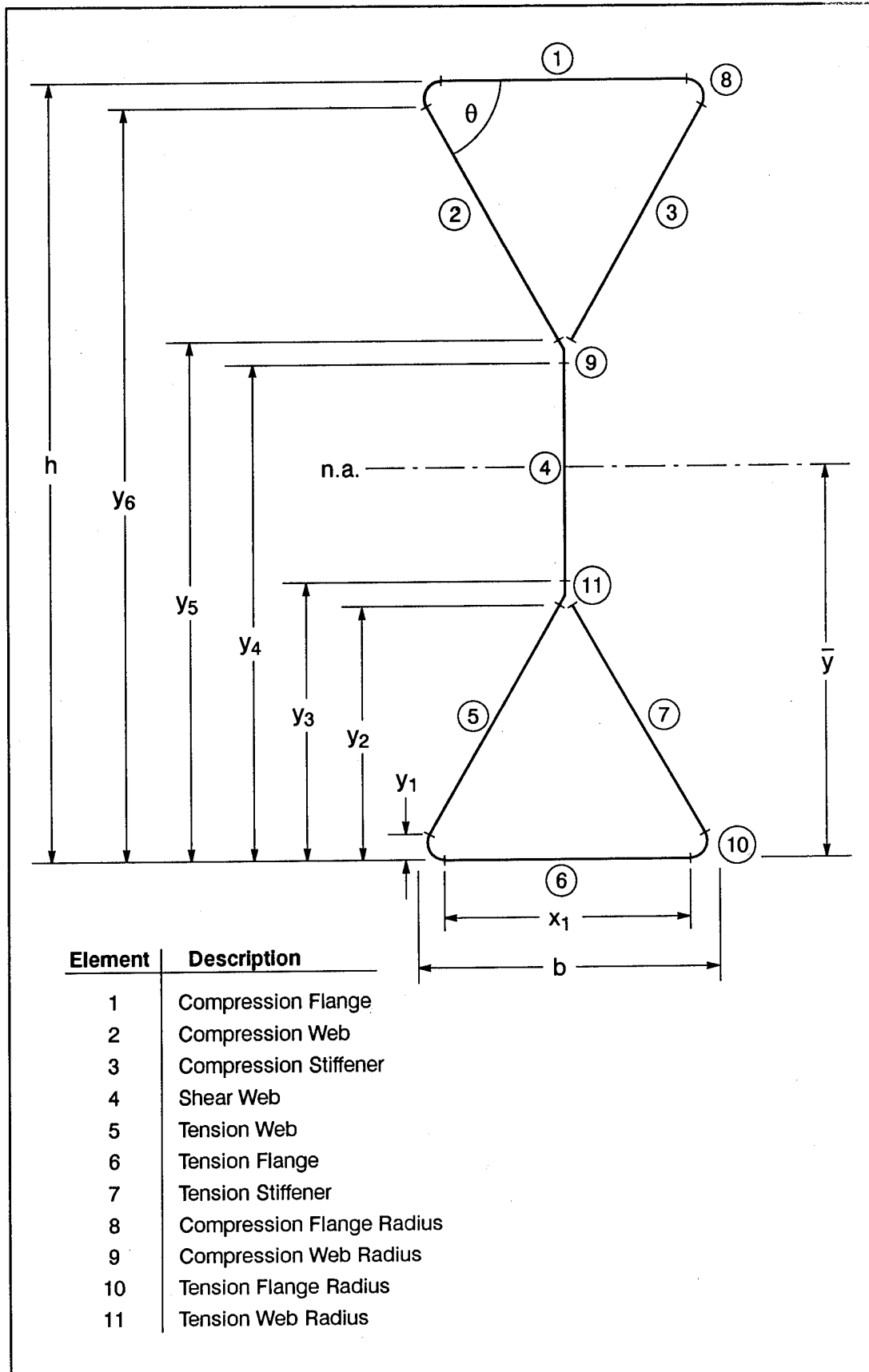


Figure B1. Dividing the "hourglass" stud into elements for analysis.

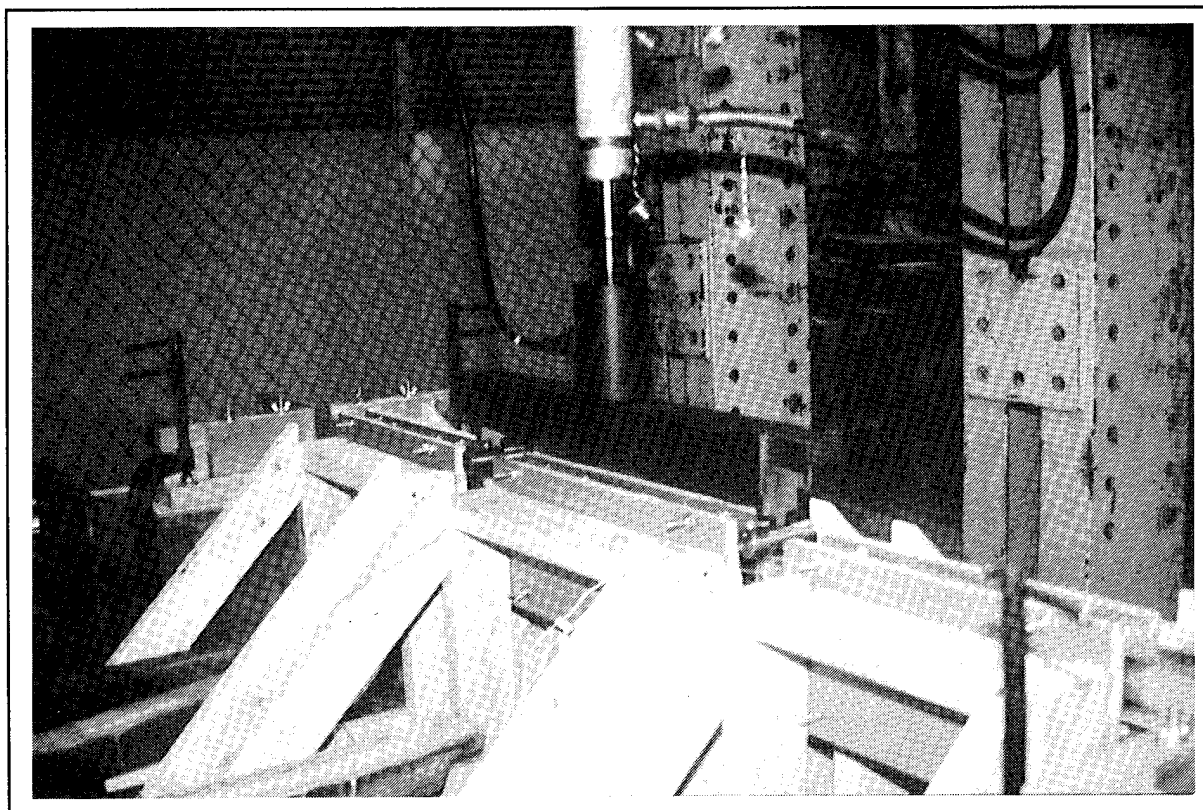


Figure B2. Test apparatus used to perform four-point bending test on "hourglass" stud.

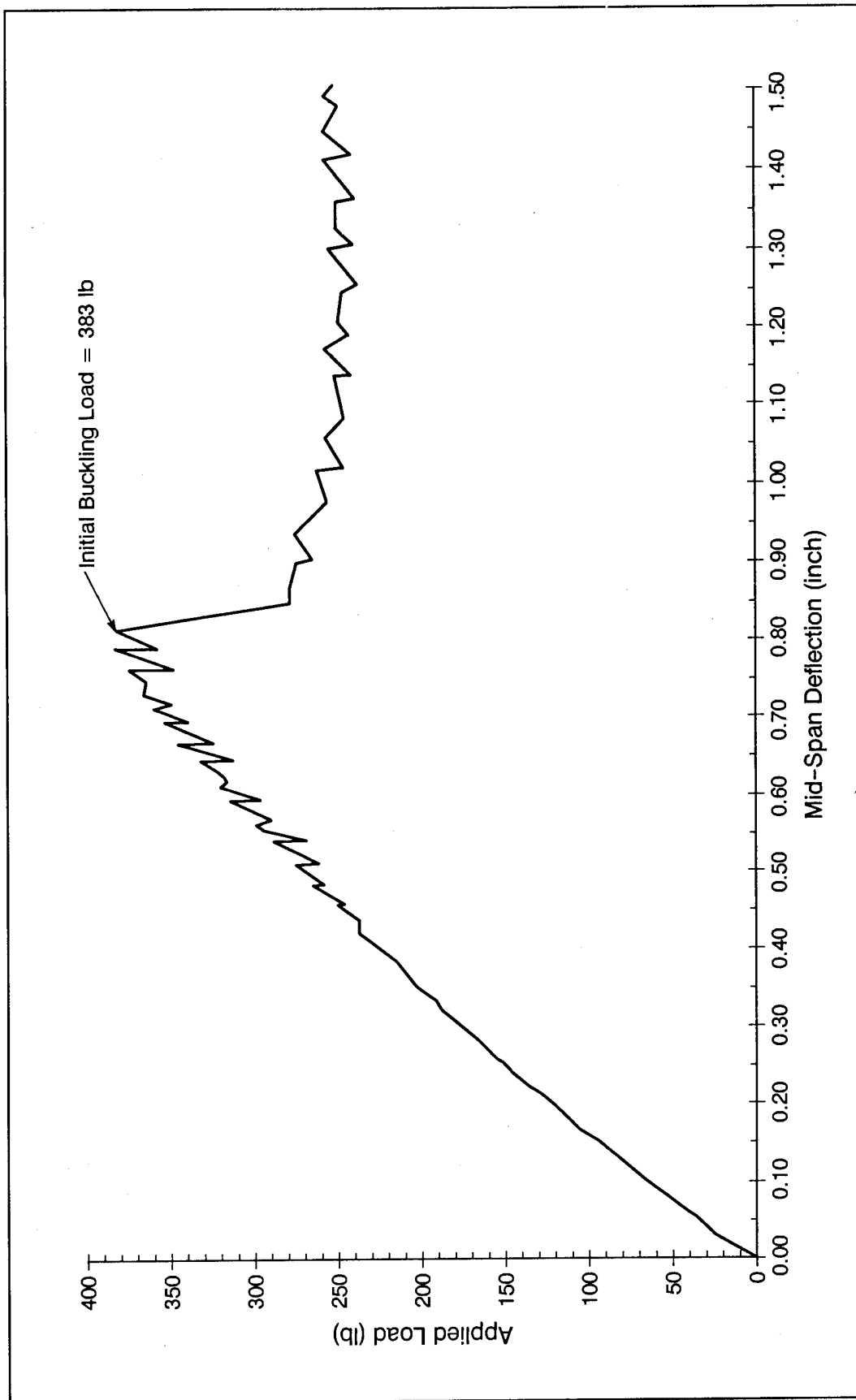


Figure B3. Applied load versus mid-span deflection.

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